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TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 354

EXPERIMENTS CONCERNING THE EFFECT OF A ROTATING CYLINDER PLACED INTO THE LEADING EDGE OF AN AIRPLANE WING

By E. B. Wolff and C. Koning

From "Rapport A.105" of the "[illegible] voor de Luchtvaart," Amsterdam.

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TESTS FOR DETERMINING THE EFFECT OF A ROTATING CYLINDER FITTED INTO THE LEADING EDGE OF AN AIRPLANE WING.*

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Summary

Experiments were performed with a wing model, to which a rotary cylinder had been fitted. The rotation of the cylinder had a remarkable effect on the aerodynamic properties of the wing. The effect of some of the essential factors was likewise investigated. We are giving the experimental results and a theoretical explanation of the phenomenon, together with a general discussion of the problems still to be investigated and the possibilities of practical application.

Introduction

The preliminary tests, made in September and October, 1924, showed that a very appreciable modification of the air flow about the wing was obtained by rotating the cylinder (Figs. 1-2). In the preliminary tests, only the value of the lift (C_y) was measured, while the revolution speed of the cylinder was not accurately determined (See N.A.C.A. Technical

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* From a preprint of Report A.105 of the "Rijks-Studiedienst voor de Luchtvaart," Amsterdam.

Memorandum No. 307).

Subsequent Tests.- During the subsequent tests, which were undertaken without any considerable changes in the original apparatus (Fig. 3), we were compelled, first of all, to determine the various values with more precision. The details regarding the method employed will be given in a future, more circumstantial report. In the meantime, it will suffice to mention that the values of C_y are accurate to within 2% and the value of C_x to within 10%.

Tests have been made:

1. With the same model (Fig. 1, model 38a), determining the drag C_x, as well as the lift C_y, both with the cylinder at rest and with it in motion, and fixing the effect of the changes in the ratio of the peripheral velocity of the cylinder to the velocity of the wind (u/v);

2. With the same model, the width of the slot between the cylinder and the fixed part of the model having been changed (C_y and the effect of u/v being determined);

3. With the same model, provided with a leading-edge piece (Fig. 1, model 38b), so as to give to the whole the shape of a normal wing (C_y and C_x being determined with the cylinder in motion and also with the cylinder at rest);

4. With the model 38b, after having closed the slot on the lower side, so as to enable the cylinder to be active only on the upper or negative-pressure side, model 38c (C_y being determined).

It is well to remember here that the only object at first was to find a combination capable of being employed on an airplane and which, in the event of the cylinder stopping, would not be too poor aerodynamically. It has already been set forth in the provisional report as to how the effect of the cylinder might be explained. Contrary to what takes place, when experiments are made with cylinders alone or in combination with small fixed bodies, it is convenient (in the case under discussion) to attribute the observed phenomena especially to the effect of the cylinder on the velocity of the air in the boundary layer on the top of the wing behind the cylinder.

The filaments of air circulating at a very short distance along the body (boundary layer) are strongly retarded by the effects of friction. This retardation may be so great that any increase in pressure along the body cannot be overcome. In this event, a counter-current will be produced in the boundary layer and the flow (filaments) will become detached from the body, forming a turbulent zone and thus producing a greater or less change in the whole aerodynamic process. On wings with a large angle of attack, this phenomenon is generally manifested

only near the trailing edge. As the angle of attack increases, the turbulent zone extends farther forward, until it finally covers the whole top of the wing. This phenomenon is accompanied by the well-known shifting of the forces in the vicinity of what is termed the "critical angle of attack." As the angle of attack increases, a point is finally reached where the lift ceases to increase and begins to decrease more or less rapidly, while the drag continues to increase strongly. If, at this point, a stronger impulse can be imparted to the boundary layer, it will be able to withstand a greater or more rapid increase in pressure. The result is that in cases where otherwise the boundary layer would be completely detached, this detachment will be avoided or at least reduced to a minimum. By this means the critical angle of attack of a wing will acquire a greater value and the coefficient of lift will also be increased. Now it has been found that the incorporation of a rotary cylinder is the very means required to give a greater impulse to the boundary layer. The cylinder will draw to its surface the boundary layer which, after reaching the fixed part of the wing, will possess, from then on, this greater momentum, which it would not otherwise have had. This explanation of the phenomenon is, moreover, corroborated by the results obtained in practice.

Results.- These are given in Figs. 4-8 and Tables I-III, the measured forces being expressed in absolute coefficients by means of the formulas

$$R_y = C_y \frac{\gamma}{g} OV^2$$

and

$$R_x = C_x \frac{\gamma}{g} OV^2$$

in which:

R_y is the lift (the component of the force of the wind perpendicular to its direction);

R_x is the drag (the component of the force of the wind parallel to its direction);

C_y and C_x respectively represent the coefficients of thrust and drag;

$\frac{\gamma}{g}$ is the specific mass of the air;

O is the surface area of the model;

V is the velocity of the wind.

In most of these tests, the various numerical values were carefully determined and the flow was also studied by means of a fine thread attached to a steel needle. The results shown in the accompanying diagrams, on the one hand, and the results of this study, on the other hand, demonstrate that the rotary cylinder causes considerable changes in the flow. This fact fully confirms the above hypothesis that the effect of the cylinder can be explained by the acceleration it communicates

to the flow of the boundary layer.

So long as there is little or no detachment or discontinuity of the boundary layer (i.e., below the critical angle of attack), there will be, even while the cylinder is rotating, a current similar to the flow about an ordinary wing. In both cases, the character of the forces must be similar. At any rate, the action of the cylinder increases the critical angle, which results in the attainment of a higher maximum coefficient of lift. It follows from Figs. 4-5 that such is actually the case. For the sake of comparison, the data have also been added for a model of an ordinary wing. The Göttingen wing profile No. 386 was chosen for this purpose, because it is very similar to the model with a leading edge. The curves of the model No. 38a (without leading edge) can be very well envisaged as the prolongation of the curves of the Göttingen profile No. 386 below the critical angle. The maximum coefficient of lift is, however, 1.215, instead of 0.64 for an ordinary wing profile, i.e., 90% higher. High lift coefficients are always coincident with a high resistance or drag. The latter is composed, in part, of a high induced drag and, in part, of a high profile drag. The induced drag of this model is shown in Fig. 4. The induced drag is necessarily high, because it depends directly on the coefficient of lift. The high profile drag is due to the fact that the boundary layer is detached from the rear portion of the top of the wing, a fact which has

been established for large angles of attack by the examination of the air flow. The cylinder, although it resists this detachment near the leading edge, is not able, however, to maintain perfect contact of the boundary layer with the whole surface of the wing. In order to obviate this disadvantage, it might be possible to employ another profile, to mount the cylinder at another point, to mount a second cylinder farther back, to increase the impulsion of the boundary layer by increasing the revolution speed of the cylinder, or by roughening its surface. The efficiency obtained with the model No. 38b (with a leading-edge piece) was much lower. The maximum coefficient of lift was 0.724, only 13% higher than for the Göttingen model No. 386. This is ascribable to the fact that the cylinder had only a small active surface (Fig. 1) and that, consequently, the boundary layer was less affected. The junction of the curves of No. 38b and of the Göttingen profile No. 386 is not entirely satisfactory, probably due to disturbances at the rear edge of the leading-edge piece, which the cylinder is unable to eliminate.

No appreciable effect was produced by covering the portion of the cylinder, which (in the model with the leading edge) is in contact, on its lower side, with the boundary layer of air (model 38c) (See Table III and compare the values obtained with model No. 38b when the cylinder was at rest). The conclusion to be drawn from this fact is that the effect of the cylinder

is confined chiefly to its upper side.

The models 38a and 38b (with the cylinder at rest) gave similar results, namely, a very small lift and a large drag. This can be explained by the considerable disturbance produced in the flow by the sharp edges of the fixed part, situated immediately behind the cylinder. The effect of these edges was clearly shown by closing the slot between the cylinder and the rear portion with paraffin, so as to obtain a continuous surface (Fig. 2). The relative agreement between the values of the coefficient of drag, when the angles of attack are equal, for the models with the cylinder either rotating or fixed, must be attributed to chance, considering that, in the first case, the induced drag and the profile drag are both large. In the second case, on the contrary, the induced drag is much less and the profile drag is much greater.

It follows from the above explanation of the effect of the cylinder on the boundary layer, that the ratio of the "peripheral velocity of the cylinder to the velocity of the wind" (u/v) may be quite insignificant (inasmuch as this ratio has little effect below the critical angle of attack), but that it may modify the value of this angle. This is clearly shown by Fig. 7, which graphically presents the results obtained for three different values of the ratio u/v for a given width of the slot. The curves incline more strongly, as the ratio u/v decreases. Analogous results were obtained for other widths

of the slot.

It was also found that a preponderant influence was exerted by the width of the slot between the cylinder and the fixed rear piece. When the ratio u/v is constant, the critical angle is reached sooner in proportion as the slot is wider. Fig. 8 furnishes a characteristic example of this. In order to understand this phenomenon, it should be observed that, in proportion as the width of the slot is increased, the portion of the boundary layer of the cylinder, which is simply lost in it, increases and the useful effect on the upper surface of the fixed part simultaneously decreases.

General Conclusions.- The effect of the adaptation of a rotary cylinder is practically the same as that of making a slot in the wing (like the slotted wing of Handley-Page). Under the circumstances, a comparison of the results obtained thus far by means of these two methods cannot fail to be of interest. For wings provided with a slot in their front portion, the maximum coefficient of lift was found to be 1.17. For wings provided with a slot in the front part and an aileron with a slot in the rear part, this coefficient was found to be 1.27.*

On examining the results obtained, several important questions arise, which have not been answered by the tests. These

* Glauert, "The Handley-Page Slotted Wing," Aeronautical Research Committee, R.& M. No. 834.

questions involve both the theoretical side of the phenomenon and the possibility of its practical application. The important theoretical points, whose solution may have considerable influence on their practical utilization, may be divided into two groups. The first group consists of those which concern the effect of the cylinder on the boundary layer, and the second group comprises those which concern the manner of utilizing the accelerated boundary layer to the best advantage. The essential factors, determining the effect of the cylinder on the boundary layer are as follows: 1, the ratio u/v of the peripheral velocity to the wind velocity; 2, the degree of roughness of the cylinder; 3, the effect of Reynolds Number. The great significance of the value of the ratio u/v has already been demonstrated by the results of the tests. The question as to whether this action has a maximum, still remains unsolved. In other words, would it be possible, by increasing this ratio, to reach a point beyond which there would be no further useful effect and, in the affirmative, what are the determining factors of this maximum? Previous to these tests, some preliminary experiments gave the impression that this maximum actually exists and that it is reached in the vicinity of 3.2, the value employed for the ratio u/v. The results of these experiments are not numerous enough, however, to warrant positive conclusions. No experiment has yet been performed for determining the effect due to the nature of the cylinder sur-

face. It is possible that a rough cylinder may act more powerfully on the boundary layer and that, due to this action, better results may be obtained. The determination of the effect of Reynolds Number likewise requires more elaborate experiments, in view of the fact that the thickness of the boundary layer and the distribution of the velocities in this layer depend on this number.*

In the second place, we have the problem of the intensive utilization of the accelerated boundary layer. Here, the shape of the wing profile and the location of the cylinder are impor-

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Von Karman, "Ueber laminare und turbulente Reibung," Zeitschr. f. Angew. Math. u. Mech., 1921, p. 233.

"Ueber die Oberflachenreibung von Flussigkeiten," published in "Vortrage aus dem Gebiete der Hydro- und Aero-dynamik," Innsbruck, 1922, p. 146.

Fuchs-Hopf, "Aerodynamik," p. 171.

Bibliography (experimental):

Burgers and Van der Hegge Zynen, "Preliminary Measurements of the Distribution of the Velocity of a Fluid in the Immediate Neighborhood of a Plane Smooth Surface" (Mededeeling No. 5, Laboratorium voor Aerodynamica en Hydrodynamica der Technische Hoogeschool te Delft).

Van der Hegge Zynen, "Measurements of the Velocity Distribution in the Boundary Layer along a Plane Surface" (Dissertatie, Delft, 1924).

Burgers, "The Motion of a Fluid in the Boundary Layer along a Plane Smooth Surface." Proceedings of the First International Congress for Applied Mechanics, Delft, 1924, p. 113.

tant, though the possibility of using more than one cylinder, or of causing, in some other manner, the wing covering to move with the air flow, is not excluded.

In this connection, it is appropriate to call attention again to the fact that the mediocre results obtained with the fixed cylinder, are ascribable to the disturbing effect of the slot. It was found by the R.S.L. (the government agency for the study of aeronautic problems)* that this prejudicial effect depends principally on the slot in the top of the wing and that the front portion of the wing is particularly sensitive. It is therefore probable that it is better to mount the cylinder farther toward the rear and that, by so doing, it would be possible to obtain better results with the fixed cylinder.

In some of the above tests, it would only be necessary to measure the forces for one model and to make a brief examination of the air flow. In others, it would be necessary to make a more thorough study of the nature of the flow. For this purpose, it would be possible to determine the pressure distribution on the surface of a model and in the boundary layer. Professor J. M. Burgers of Delft has kindly consented to under-

* Verslagen en Verhandelingen van den Rijks-Studiedienst voor de Luchtvaart, Vol. II, 1923: Report A.51, "Expériences sur un mécanisme réduisant la longueur de roulement et de vol plané à l'atterrissage des avions (N.A.C.A. Technical Memorandum No.272); Report A.29, "Expériences sur l'influence d'une échancrure dans le bord d'attaque de l'aile de l'avion Fokker F III sur les caractéristiques aérodynamiques (N.A.C.A. Technical Memorandum No. 103).

take these investigations with the model employed for this report.

As regards the practical applications, it is especially important to investigate the cases where a high value of the coefficient of lift is desirable, i.e., in taking off, in climbing and in landing. The provisional results show no improvement in climbing, because, for the climbing speed, the maximum value of C_y^3/C_x^2 is the most important factor and is attained at small values of C_y. For taking off and landing, it is important, however, to have a high maximum value for C_y, which produces, for a given wing loading, a low minimum flight speed and consequently shortens the distance required for taking off. The cylinder may also help where the local disturbance of the flow must be avoided without its being necessary to have a high value of C_y. Some improvement of the profile drag might perhaps be obtained for large angles of attack (not, however, exceeding the critical angle) by preventing the detachment of the air flow on the rear portion of the upper surface of the wing, by introducing a cylinder in this vicinity. There would be many other useful applications, as, for example, to prevent the detachment of the air flow at the edges of a cutaway in a wing, or to prevent a sudden detachment of the flow in the vicinity of the critical angle of attack, either for the wing or the ailerons or the stabilizer.

Translation by Dwight M. Miner,
National Advisory Committee for Aeronautics.

Table I.

Model No. 38a (without leading edge)

Width of slot=0.5 mm(0.02 in.); u/v = 3.2; v=5 m(16.4 ft.)per sec.

Cylinder in motion			Cylinder at rest		
α	C_y	C_x	α	C_y	C_x
11.0	0.7065	0.0875	10.3	0.2215	0.122
16.0	0.7775	0.127	15.4	0.257	0.1625
21.3	0.9305	0.169	20.4	0.264	0.218
26.4	0.993	0.201	25.5	0.3575	0.246
31.6	1.125	0.249	30.5	0.375	0.2585
36.6	1.1995	0.280	35.5	0.3935	0.3605
41.7	1.215	0.395	40.6	0.401	0.408
46.5	1.0735	0.356	45.6	0.4085	0.4695
51.6	1.146	0.4165	50.6	0.4085	0.5085

α = angle of attack.

C_y = coefficient of lift.

C_x = coefficient of drag.

Table II.

Model No. 38b (with leading edge)

Width of slot=0.5 mm(0.02 in.); u/v = 3.4; v=5 m(16.4 ft.)per sec.

Cylinder in motion			Cylinder at rest		
α	C_y	C_x	α	C_y	C_x
15.9	0.6125	0.123	15.4	0.297	0.173
18.5	0.6605	0.134	18.0	0.330	0.2025
21.1	0.724	0.163	20.5	0.3475	0.2045
23.5	0.6825	0.212	23.0	0.3335	0.216
25.9	0.5895	0.2415	25.5	0.357	0.232

α = angle of attack.

C_y = coefficient of lift.

C_x = coefficient of drag.

Table III.

Model No. 38c.

Width of slot=0.5 mm(0.02 in.); u/v = 3.6; v=5 m(16.4 ft.)per sec.

Cylinder in motion.	
α	C_y
15.8	0.5475
25.8	0.5185
30.8	0.540

α = angle of attack.

C_y = coefficient of lift.

d = 1000 mm (39.37") g = 37 mm (1.46")
e = 200 mm (7.87") h = 132 mm (0.52")
f = 185 mm (7.28")

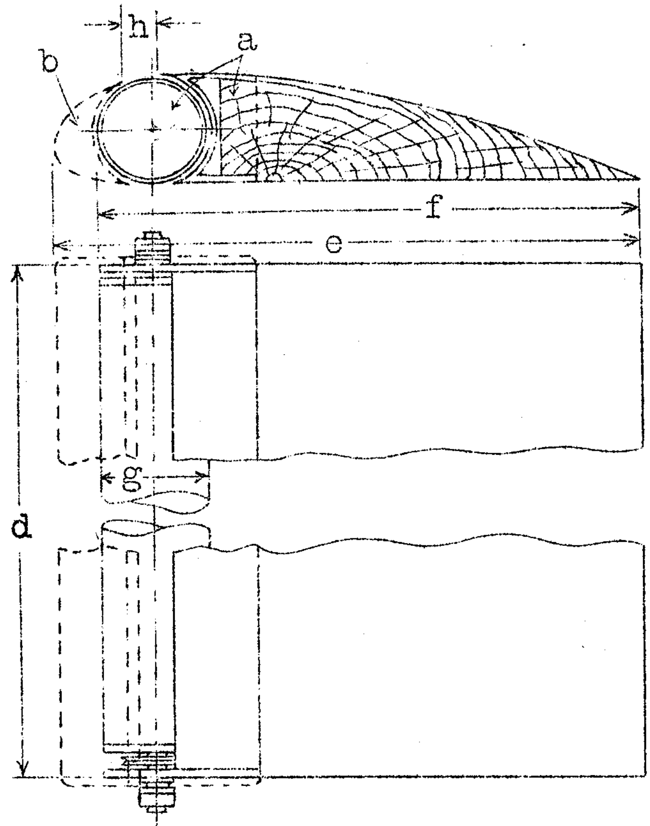
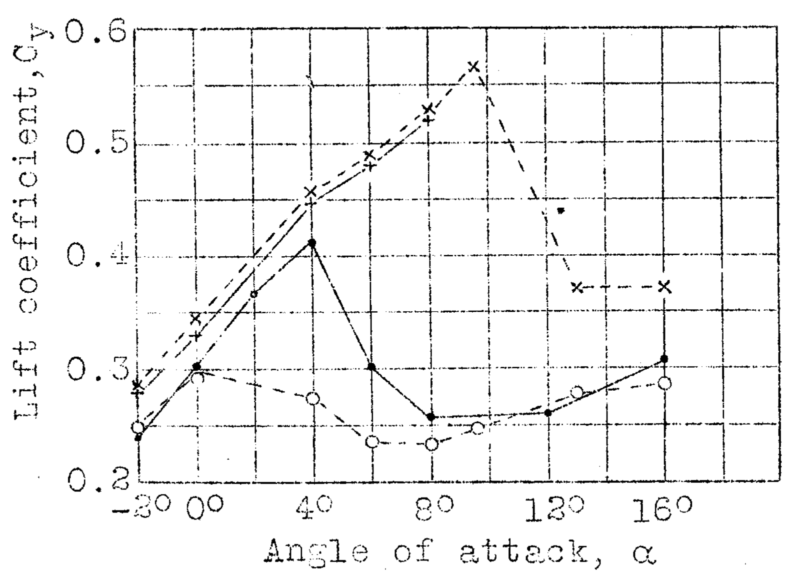


Fig.1 Model No.38, a, without leading edge. b, with leading edge.



——•—— Cylinder at rest, slot closed.
- - -○- - - " " " , " open.
——+—— " in motion.
- - -×- - - " " " , peripheral velocity greater.

Fig.2 Results of the preliminary tests.

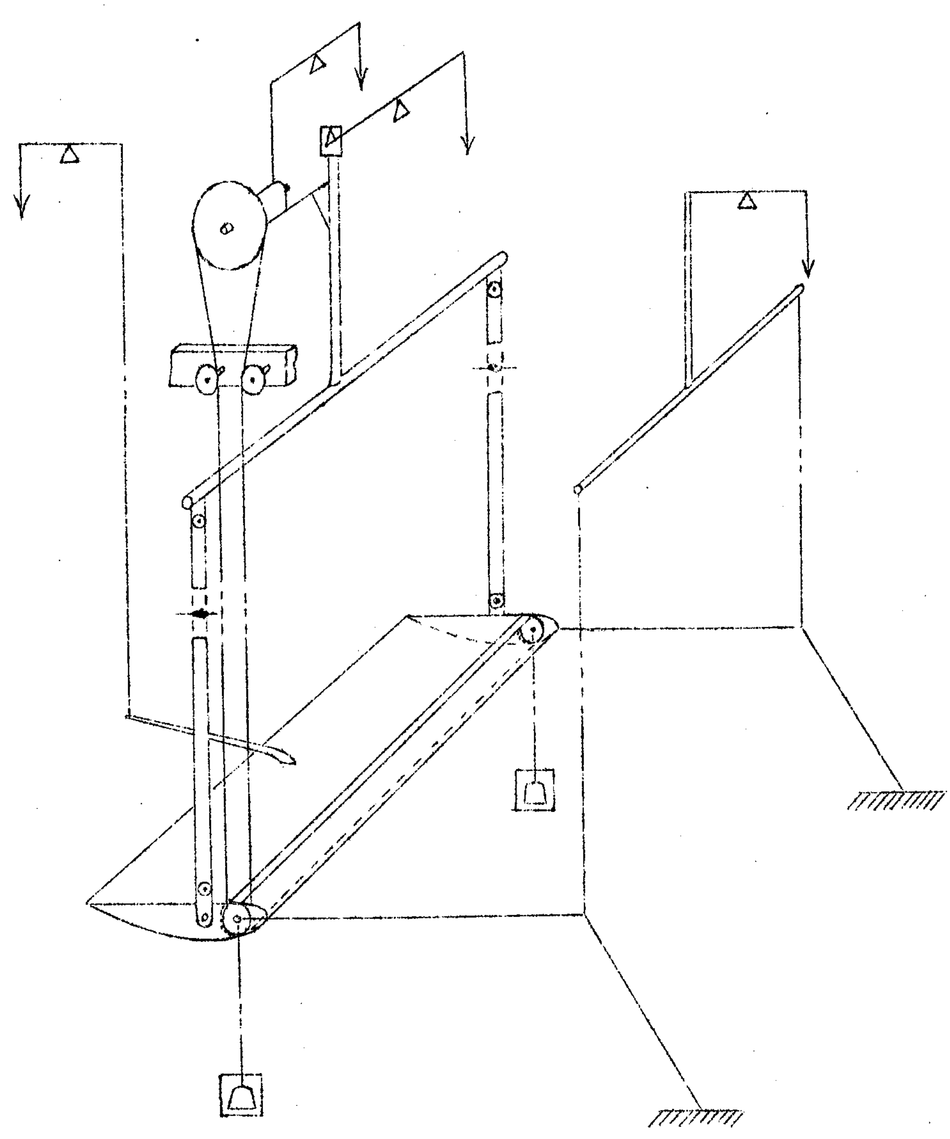


Fig.3 Method of measuring.

——⊙——	Model No.38a(without leading edge)cylinder in motion
——○——	" " " (" " ") " at rest
----+----	" " 38b(with " ") " in motion
----×----	" " " (" " ") " at rest
---△---	Göttingen model No.386
—-—-—	Induced drag for model No.38a

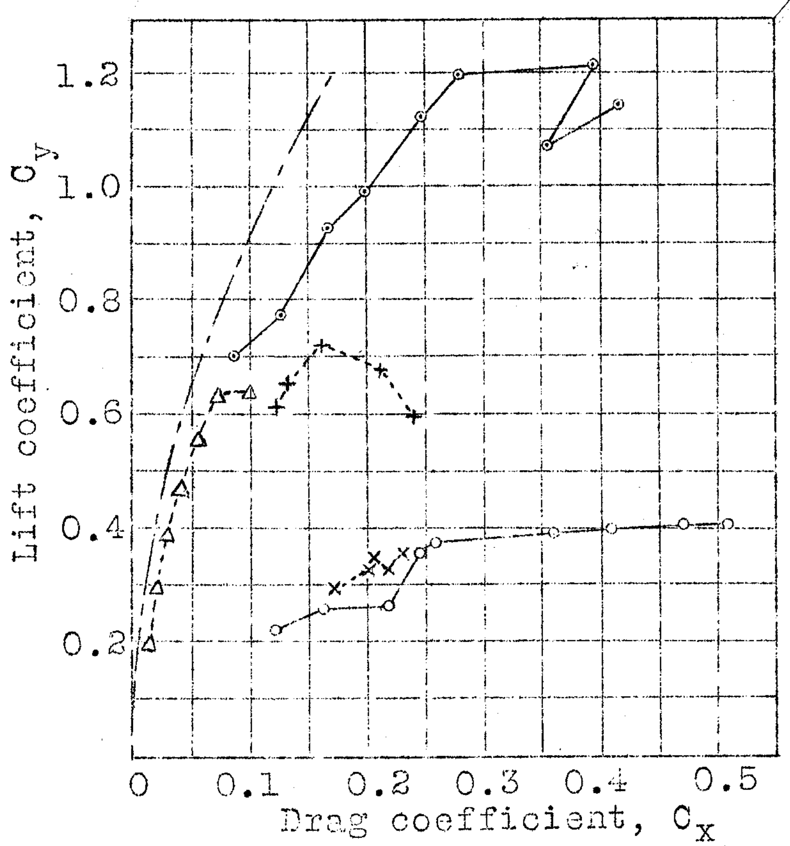


Fig.4 Coefficients of lift (C_y) and drag (C_x) for models No.38a and 38b.

—⊙— Model No.38a(without leading edge)cylinder in motion
- - o - - " " " (" " ") " at rest
—+— " " 38b(with " ") " in motion
- - x - - " " " (" " ") " at rest
—△— Göttingen model No.386

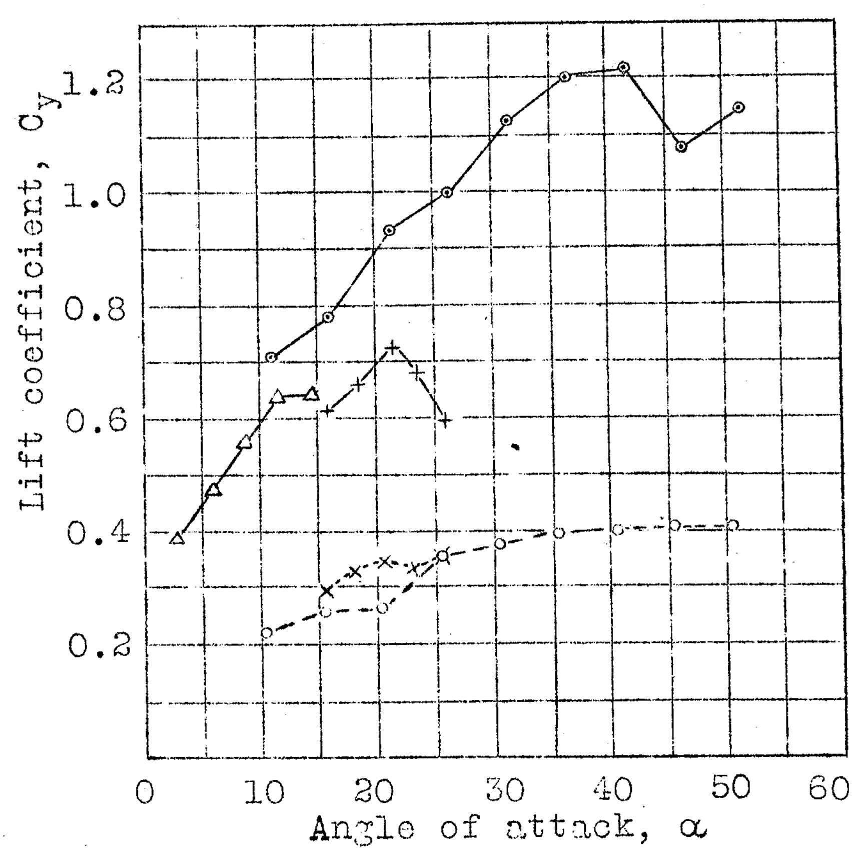


Fig.5 Coefficients of lift (C_y) for models No.38a and 58b.

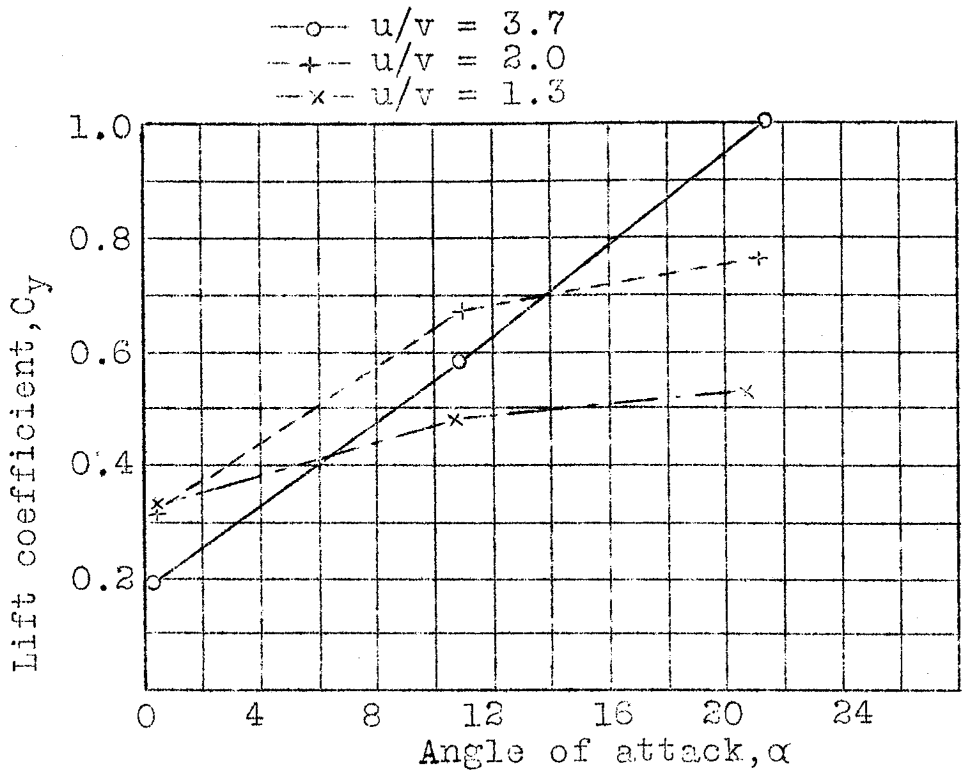


Fig.7 Effect of ratio (u/v) of peripheral velocity to velocity of wind. Model No.38a (without leading edge). Width of slot, 1mm (0.394 in.)

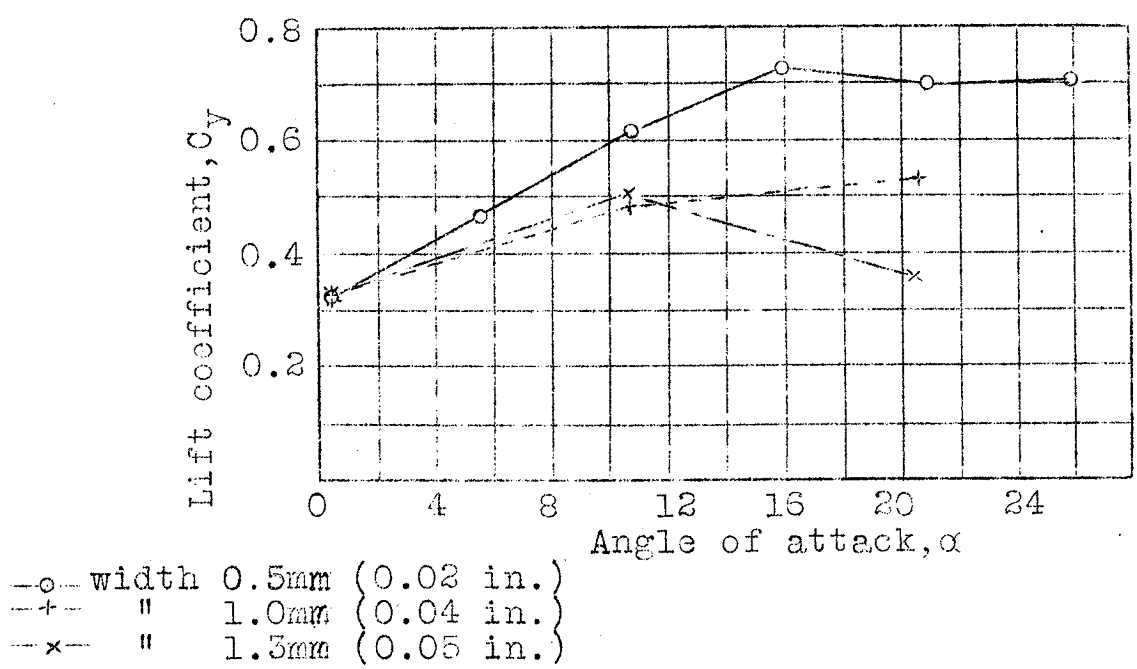


Fig.8 Effect of width of slot. Model No.38a (without leading-edge piece), u/v = 1.3.

—⊙— Model No.38a(without leading edge)cylinder in motion
- -○- - " " " (" " ") " at rest
---+--- " " 38b(with " ") " in motion
....×.... " " " (" " ") " at rest
—△— Göttingen model No.386

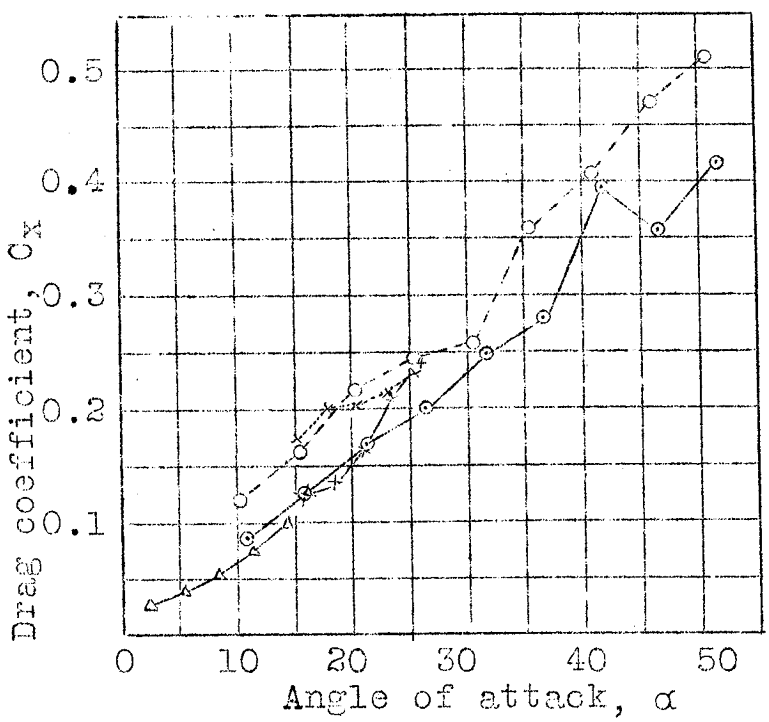


Fig.6 Coefficients of drag (C_x) for models No. 38a & 38b.